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Stochastic Predictions of Sediment Yields from Small Coastal Watersheds in Oregon, U.S.A.

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STOCHASTIC PREDICTIONS OF SEDIMENT YIELDS FROM SMALL COASTAL WATERSHEDS IN OREGON, U.S.A.

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ABSTRACT

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For many streams in the Pacific northwestern U.S.A., nearly all sediment is transported during brief, distinct runoff events. The event sequence can be stochastically described by combining a Poisson process, a flow frequency analysis, and a sediment rating curve. The model is used to predict long-term distributions of annual suspended-sediment yields from two small watersheds in the Oregon coast range.

For these watersheds, observed annual yields appear to be less variable than would be predicted from random sums of individual storm event yields. The discrepancy between synthetic and observed yields is probably due to the controls imposed by sediment sources.

INTRODUCTION

In the Pacific northwestern U.S.A., increased erosion and sedimentation due to logging activities is a prime environmental concern. Unfortunately, it is often difficult to detect changes in sediment production caused by timber harvest in small watersheds, largely because sediment yields are highly variable and stochastic in time.

To explore the variability problem, a simple stochastic model of sediment yield has been applied to data from two small Oregon coast range watersheds. The model combines a runoff event frequency analysis, an event-generating process, and an empirical relation between sediment yield and discharge, to generate sequences of sediment yield events. Yields from individual events are then summed to produce annual yields.

This approach is essentially a stochastic extension of the duration curve—sediment rating curve method of estimating watershed sediment yield (Vanoni, 1975). Instead of a single mean annual yield, the stochastic model produces a long-term frequency distribution of annual yields. The frequency distribution expresses the year-to-year variability in yield which results from

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the intermittent, stochastic nature of large runoff events. Observed and model-generated yield distributions are compared for the two watersheds. When sediment–discharge relations are stable over time, the model gives a reasonable prediction of long-term yield probabilities.

Second to stream discharge, sediment source dynamics are probably the major determinant of sediment yield fluctuations. But sediment sources are very difficult to quantifiy, and their dynamics are poorly understood (Wolman, 1977). Therefore, the sediment–discharge residuals were explored for evidence of changing sediment availability, with the hope that this evidence could improve the model. This effort had little success. However, at a coarser time scale, the difference between observed and synthetic annual yields seemed best explained by the regulating effect of sediment supplies.

MODEL DESCRIPTION AND BACKGROUND

The model is based on the selection of discrete events of short duration, during which discharge exceeds some threshold. The events are defined in such a way that estimates of individual sediment yields are available for some set of observed events. Discharge could be measured as daily mean flow or instantaneous peaks. In either case, the discharge threshold Q_T must be set high enough so that events are stochastically independent (Yevjevich, 1972). At the same time, it must be set low enough to capture all events which contribute significant amounts of sediment.

Next, a compound stochastic process is used to model the occurrence times of events and their discharge levels (Todorovic, 1978; see also Yevjevich, 1972; Gupta et al., 1976). Let $N(t)$ = number of events which occur in the interval $[0,t]$. In this study, $N(t)$ was described by a Poisson counting process, with parameter λ, such that $E[N(t)] = \lambda t$ (Todorovic, 1978). That is,

$$P[N(t)=k] = e^{-\lambda t}\frac{[\lambda t]^k}{k!}, \qquad k = 0, 1, 2, \ldots; \quad t \geqslant 0 \tag{1}$$

With slight changes in eq. 1, the parameter λ can be made a continuously-varying function of time. For this study, it was sufficient to take λ as a seasonally-piecewise constant function. In some cases, a negative binomial distribution may better represent event frequencies (Cunnane, 1979).

Define Q as the discharge rate and $Q^* = Q - Q_T$ as the exceedance level. Then the Q^*-values for events are treated as independent random variables with distributions which are identical within seasons of the year. For this study, the two-parameter gamma distribution was chosen to model Q^*. The probability density function is:

$$f_{Q^*}(q) = \alpha^\eta q^{\eta-1} e^{-\alpha q}/\Gamma(\eta), \qquad q,\alpha,\eta > 0 \tag{2}$$

where $\Gamma(\eta)$ is the gamma function (Haan, 1977). The gamma distribution

was chosen primarily for convenience; computer software was available for sampling from the cumulative distribution function. Other flood frequency distributions, such as the lognormal or log Pearson III, might have performed equally well.

Logarithms of discharge level, Q, and sediment yield, Y, per event, were related by a linear regression model, called a sediment rating curve. Sediment—discharge relationships are assumed stationary over time through the use of constant regression parameters.

The preceding approach is not new. The prediciton of sediment yields via the product of a rating curve and a flow duration curve is a standard technique (Vanoni, 1975; U.S.D.A., 1975). The model may be viewed as a simplification of the model of Woolhiser and Todorovic (1975), in which runoff and sediment yield events are generated by a stochastic process for rainfall. These authors also suggest that short sediment yield records can be combined with longer runoff records to improve estimates of mean sediment yield, and they present an example for two agricultural watersheds. Renard and Lane (1975) take a similar approach, with a different stochastic process for runoff events and a deterministic discharge—sediment relationship. Several of the statistical checks used in this study were suggested by the rainfall-event study of Croley et al. (1978).

MODEL APPLICATION

The model was applied to two experimental watersheds in the Oregon coast range which were monitored for 15 years as part of the Alsea watershed study. Between 1958 and 1973, stream discharge and suspended sediment yield were sampled in Flynn Creek (202 ha), and Needle Branch (75 ha). Nearly all of the annual precipitation is rainfall between November and May, dominated by intermittent, frontal storms (Harr et al., 1975). Throughout the Alsea study, Flynn Creek was used as a control and remained in its natural state. In 1965, logging roads were constructed into Needle Branch and the watershed was 82% clear cut between March and November of 1966.

Daily mean discharge ($ft.^3/s$) and daily suspended-sediment yield (t/day) were recorded for the two watersheds. Fourteen complete water years (October 1—October 1) of data were collected by the U.S. Geological Survey and provided by S.F. Kaputska. Sampling methods were described by Harris (1977). Several other hydrological and biological variables also were monitored during the Alsea project. For comprehensive descriptions of the study, see Brown and Krygier (1971), Harr et al. (1975), Harris (1977), and Beschta (1978).

The preceding papers generally agreed that instantaneous peak discharges and annual sediment yields were significantly increased in Needle Branch following logging. As a result, Needle Branch was viewed in this study as a "disturbed" system during the water years 1967—1973 and "undisturbed"

system during the water years 1960–1967. Model parameters for Needle Branch were estimated separately for the two periods, while the Flynn Creek parameters were based on the unbroken record from 1960–1973.

Selection of events

High-flow events and their associated sediment yields were identified using the scheme of Fig. 1. A flow threshold, Q_T, was set, and flow and sediment data from all days with daily flow $<Q_T$ were discarded. An arbitrary event k, was defined as a continuous sequence of days during which the mean daily flow exceeded Q_T. The discharge measurement, Q_k, was taken to be the largest mean daily flow during event k. Sediment yield, Y_k, is the sum of the daily yields over the duration of event k. Fig. 1 also defines other variables of interest: the calendar time, T_k, of the event, the duration, D_k, and the time interval, I_k, since the previous event.

After some experimentation, $Q_T = 0.16\ m^3\ km^{-2}\ s^{-1}$ ($=15\ ft.^3\ mi.^{-2}\ s^{-1}$) appeared the best choice. Over the 14-yr. record in Flynn Creek, there were 108 high-flow events during which $Q > Q_T$, thus providing a large enough sample size for most statistical purposes. For Flynn Creek, the stochastic independence of the series Q_k, $k = 1, \ldots, 108$ was checked. A sign test (Miller and Freund, 1977) was made of the departure of individual Q_k's from the yearly median flow for each of the 14 years. In addition, a sign test was made on the departure of Q_k's from the 14-yr. median flow. In none of the fifteen tests could the null hypothesis of sequential independence be rejected

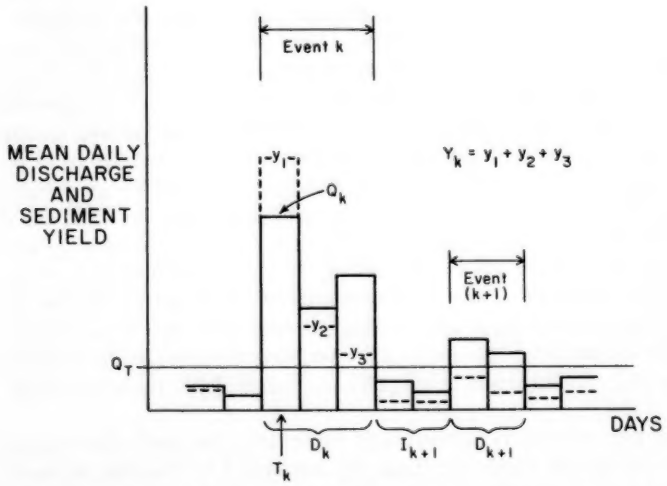


Fig. 1. Selection of high-flow events from a continuous record of daily mean values. —— = streamflow; – – – = sediment yield.

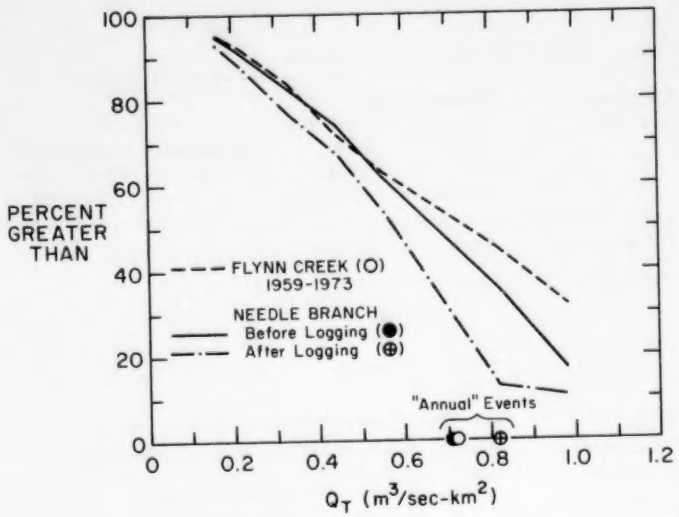


Fig. 2. Cumulative percent of total suspended sediment due to discharges greater than Q_T.

with $p < 0.05$. Throughout, observed significance levels, or "p-values" (Snedecor and Cochran, 1967) have been reported. A level of $p = 0.05$ was used in hypothesis testing.

Fig. 2 shows the effect of the selected flow threshold on sediment yield. In both Flynn Creek and Needle Branch, more than 93% of the total sediment yield could still be accounted for after discarding data from all days when $Q < 0.16\ m^3\ km^{-2}\ s^{-1}$. The days of high flow ($Q > Q_T$) constitute ~11% of the total period of record. The figure makes another important point: annual peak flow events contributed only ~50% of the total sediment yield from the two streams. Thus, even if flow and sediment records were long enough to construct models based on annual peak flows, such models would significantly underestimate sediment production.

Occurrence and intensity of events

The year was divided into four 91-day seasons, with $t = 0$ = October 1, the beginning of the standard water year. Then λ was estimated from the data for each of the four seasons. Because a Poisson process has independent increments (Cox and Miller, 1965) the probability density function for $N(t)$, $0 \leqslant t \leqslant 364$ days, could be easily pieced together, using the seasonal parameters.

Estimates of λ for each season were obtained by calculating $\bar{n}_e$ = the average number of events during the season, over the total length of record, and setting $\lambda = \frac{1}{91}\bar{n}_e$ (Haan, 1977). The resulting theoretical Poisson model was

TABLE I

Parameter estimates and goodness-of-fit tests for flow model

	Total number of events	Poisson model			
		$1/\lambda_F$ fall (days)	$1/\lambda_W$ winter (days)	number of χ^2-tests	number of tests with $p > 0.05$
Flynn Creek	107 (14 yr.)	36.4	20.9	8	6
Needle Branch (pre-log) (model *1*)	64 (7 yr.)	42.5	18.5	2	1
Needle Branch (post-log)	74 (7 yr.)	19.7	18.5	2	2

	Total number of events	Exceedance level (Q^*) (gamma distribution)			
		η	α	mean exceedance η/α (m^3/km^2-s)	KS test
Flynn Creek	107 (14 yr.)	0.72	3.35	0.215	$p > 0.10$
Needle Branch (pre-log) (model *1*)	64 (7 yr.)	0.70	3.17	0.221	$p > 0.10$
Needle Branch (post-log)	74 (7 yr.)	0.85	3.02	0.281	$p > 0.10$

compared with the data by plotting histograms of observed vs. expected number of events in 30-, 60-, 90- and 180-day intervals (Todorovic, 1978). The agreement between the two curves in each pair was tested with the χ^2-statistic for as many pairs as the sample sizes would permit.

For the exceedance levels, Q^*, the parameters of the gamma distribution were estimated with the maximum likelihood method described by Haan (1977). Following parameter estimation, the goodness-of-fit of the distribution was tested with the Komolgorov—Smirnov (KS) statistic.

The seasonal analysis of events revealed that, out of 118 events in 14 years on Flynn Creek, none occurred during the summer period, and only ten occurred during spring. In Needle Branch, seventeen out of 155 events occurred in the spring and one in the summer. Also, in both streams, the spring and summer events contributed less than 2% of the total sediment yield. As a result, the flow and sediment models were fitted and checked for the fall and winter periods only.

The model was further simplified when the seasonality of exceedance levels was checkd for Flynn Creek. A Mann—Whitney rank test (Snedecor and Cochran, 1967) was used to test whether fall and winter values for Q^*

were different. The null hypothesis could not be rejected with $p < 0.10$. Hence, for both streams fall and winter values for Q^* in fitting the gamma distribution were pooled.

Table I gives the parameter estimates and goodness-of-fit statistics for eqs. 1 and 2. With reservations about the power of the goodness-of-fit tests (Haan, 1977), the Poisson and gamma models were accepted as adequate to describe the flow events.

Modeling sediment

The sediment rating curve is written as:

$$\ln Y = \ln a + b \ln(Q^* + Q_T) + \ln \epsilon \tag{3}$$

where $(\ln \epsilon)$ represents the residuals in the regression. The model was fitted to the (Q, Y) data from the event records of each stream. Results are given in Table II. The variance of the regression residuals provide an estimate of the absolute variability in sediment yields for a given high-flow event. If the residuals are normally distributed with zero mean, then the ϵ's are lognormal with geometric mean = 1 and "geometric" standard deviation, $\exp[\sigma_{\ln\epsilon}]$ (Aitchison and Brown, 1957). In other words, the residual value ϵ falls within the interval $[\exp(-\sigma_{\ln\epsilon}), \exp(\sigma_{\ln\epsilon})]$, with the same probability as that associated with the limits $\pm\sigma$ in a conventional normal distribution. Table II gives the approximate 95% confidence intervals for the three regressions. Exact confidence limits for point estimates can be easily found (e.g., Neter and Wasserman, 1974).

As Table II shows, even though r^2-values are quite high, the regression model still contains a fair amount of uncertainty; for a given flow level, sediment yield can be predicted only to within factors between ~3 and 5. A good share of this uncertainty is due to changing sediment availability, which is not considered in eq. 3. As Guy (1964) demonstrated, these changes can sometimes be seen as nonstationarities in the residuals of the sediment

TABLE II

Regression parameters and confidence limits for yields—discharge model, $\ln Y = \ln a + b \ln(Q^* + Q_T) + \ln \epsilon$

	a	b	r^2	$\sigma^2_{\ln\epsilon}$	~95% CI $[\exp(-2\sigma_{\ln\epsilon}), \exp(2\sigma_{\ln\epsilon})]$
Flynn Creek	122.2	3.52	0.90	0.38	[0.3, 3.4]
Needle Branch (pre-log) and (models *1* and *2*)	49.0	3.28	0.86	0.64	[0.2, 5.0]
Needle Branch (post-log)	60.9	2.58	0.74	0.80	[0.2, 6.0]

TABLE III

Nonstationarity of residuals from rating curves in Table II — significance levels are for tests of zero correlation

(a) Seasonal trends — Flynn Creek, 107 events — logarithmic transformations used to induce normality

	Indicator variables	Hypothesized correlation	Correlation coefficient
$\ln \epsilon$ vs.	(event duration)	(+)	0.21 ($p > 0.05$)
$\ln \epsilon$ vs.	ln(interval between events)	(+)	0.20 ($p > 0.05$)
$\ln \epsilon$ vs.	(elapsed time since previous larger event)	(+)	0.18 ($p < 0.05$)
$\ln \epsilon$ vs.	(elapsed time since Oct. 1, start of rainy season)	(−)	−0.09 ($p < 0.05$)

(b) Long-term trends — rank correlation between residuals and time elapsed since beginning of record

	Spearman's rank correlation coefficient	Number of events
Flynn Creek	0.07 ($p > 0.05$)	107
Needle Branch (pre-log)	0.43 ($p < 0.01$)	64
Needle Branch (post-log)	−0.60 ($p < 0.01$)	74

rating curve. Therefore the residuals both for seasonal fluctuations and for long-term trends were explored.

A seasonal cycle of sediment storage and washout was hypothesized for the undisturbed watershed. During summer periods of low flow, inorganic sediment should accumulate. A significant portion of the suspended load in the undisturbed streams is organic (R. Beschta, pers. commun., 1980), and autumn leaf fall should bring stored sediment to its maximum level. This sediment pool should then be gradually depleted during the high runoff of the late-fall and winter rainy seasons, reaching its minimum in the early summer. During the seasonal washout period, increasingly intense runoff events should each pick up sediment at a new, higher level on the stream banks; this sequence of events should show sediment yields greater than those predicted by an overall sediment rating curve.

To test these hypotheses, the Flynn-Creek rating curve residuals were correlated with possible short-term indicators of sediment availability (Table III). The correlation coefficients in Table III have the correct hypothesized

sign, but they are, at best, marginally significant. For the chosen event sequence, seasonal accumulation and flushing of stored sediment do not strongly influence the sedimented—discharge relation.

In apparent contradiction, Beschta (1978) showed strong evidence of seasonal sediment flushing, based on the same data. Working with monthly mean discharge and concentration, he found a significant downward shift in the Flynn Creek sediment rating curves for the months following the yearly peak flow, compared with those before the peak. The opposing results suggest that only major, infrequent events can alter storage enough to affect sediment—discharge relations. In any case, a regular seasonal cycle in the sediment—discharge relation would be averaged out in calculating annual totals, and annual yield predictions would not be biased by using a non-seasonal sediment rating curve in the model.

Long-term trends in the residuals were also explored with correlation. Previous studies (Brown and Krygier, 1971; Beschta, 1978) showed that annual sediment yields in Needle Branch increased immediatly after logging. The sharp increase was then followed by a gradual decline to pre-logging levels as vegetation became re-established on the watershed (Beschta, 1978). The decline should appear as a decreasing trend in the residuals of the sediment rating curve. Since Flynn Creek was undisturbed throughout the study, no such trend would be expected in its sediment—discharge relationship.

Table III, (b) gives rank correlation coefficients (Snedecor and Cochran, 1967) between residuals and their temporal position in the event record. Only Flynn Creek showed no long-term trend. The post-logging years in Needle Branch show the expected decreasing trend, while the pre-logging years showed a weaker, but still significant, trend of yields per unit discharge increasing over time. The increasing yield trend suggests that available sediment, in excess of exported material, was gradually accumulating in Needle Branch over the 7-yr. pre-logging period.

In summary, there were no strong seasonal patterns in the Flynn Creek sediment—discharge relation. The event record for Flynn Creek also showed no long-term trend in rating curve residuals. Sediment yields per unit discharge in Needle Branch, however, showed in increasing trend during the seven pre-logging years, and a stronger decreasing trend during the seven post-loging years. Becasue of the nonstationarities in the Needle Branch records, predictions made by the stationary model must be interpreted with care.

Simulation method and results

Synthetic sequences of streamflow and sediment yield were generated from the model and compared with data. For each water year, the simulation first produced a set of event occurrence times, $t_1, t_2, \ldots, t_k$, measured in days after October 1. Interarrival times of a Poisson process are exponentially distributed (Cox and Miller, 1965). Hence, in the simulation the t_i's

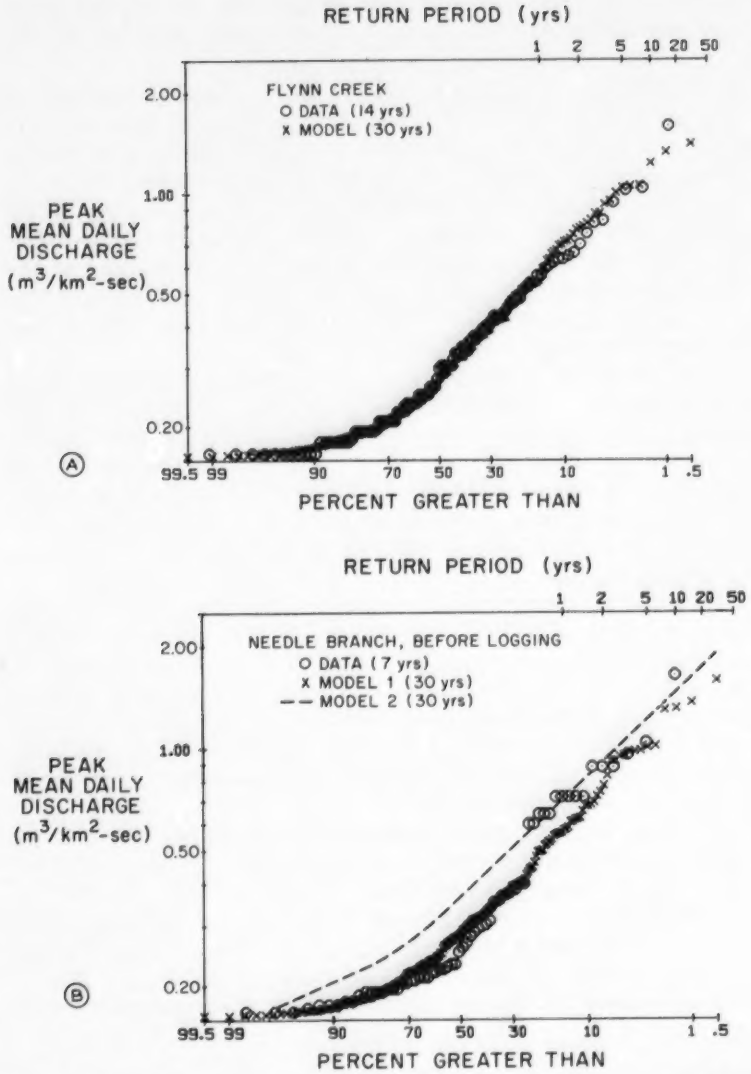


Fig. 3. Streamflow: Model vs. data. (a) Flynn Creek; and (b) Needle Branch — before logging. Model parameters from Tables I and II.

were generated sequentially by selecting random interarrival times from an exponential distribution, with parameters λ_F or λ_W, as appropriate. The selection was terminated at time t_k if $t_{k+1} > 182$ days.

For each yearly sequence, exceedance levels $Q_1^*, Q_2^*, \ldots, Q_k^*$ were then

chosen from a gamma distribution with parameters from Table I. Corresponding yields $Y_1, Y_2, \ldots, Y_k$, were generated, using eq. 3 and Table II. Random shocks, $\ln \epsilon_i$, were provided by a zero-mean Gaussian process with variance $\sigma^2_{\ln\epsilon}$. Finally, the simulation calculated a total annual yield:

$$Y_A = \sum_{i=1}^{k} Y_i \tag{5}$$

The sequence was repeated for simulated periods up to 100 yr.

Fig. 3 compares historical flow levels to the synthetic values for the unlogged systems, and Fig. 4 shows predicted vs. observed annual yields, Y_A, for all three cases. The flow model for the post-logging period in Needle Branch (not shown) fits the data visually as well as in the Flynn Creek case (Fig. 3A). In each of Fig. 4A, B and C, respectively, the observed and simulated annual yield distributions were compared with the KS statistic. In all cases, the empirical and model curves were not significantly different ($p < 0.20$).

For Flynn Creek, the two-parameter distribution did a good job of representing actual streamflow levels (Fig. 3A), and the resulting predictions of annual yield (Fig. 4A) at a given return interval were accurate to within a factor of 2. The same level of accuracy was apparent in the annual yield predictions for Needle Branch after logging (Fig. 4C).

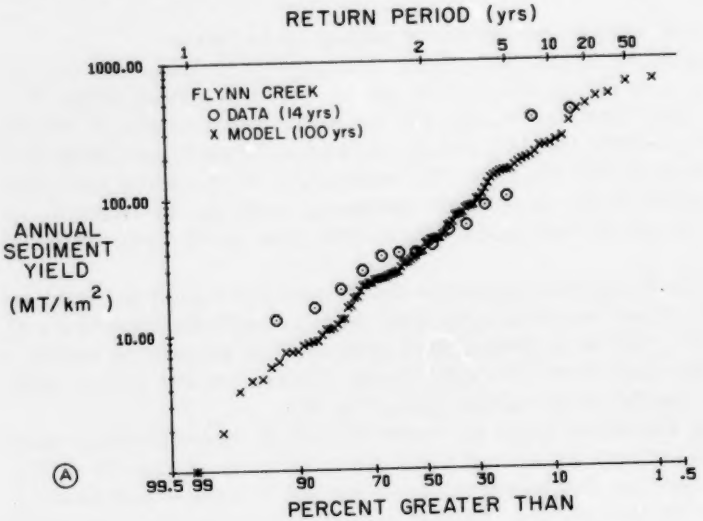
Figs. 3B and 4B, which apply to Needle Branch in its undisturbed state, illustrate the sensitivity of annual yield predictions to a poor fit in the upper tail of the flow frequency curve. In Fig. 4B it appears that model *1* consistently underestimates the observed annual yields, and this bias would not result from the increasing trend in the sediment rating curve residuals. The explanation is found in Fig. 3B. The exceedance level gamma distribution for model *1* employed parameters (Table I) which were estimated with the maximum likelihood method. As Fig. 3B shows, the more numerous lower flows dominated the curve fit. The frequency of flows greater than $0.5\,m^3/km^2$-s was then underestimated, due to a dog-leg in the empirical exceedance distribution. Since these higher flows carried a major portion of the total load, annual yields based on model *1* were underestimated.

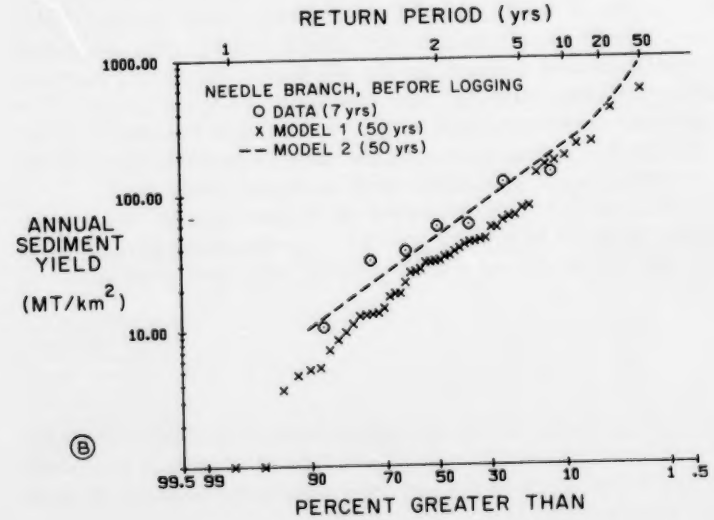
Model 2 (Fig. 3B) uses gamma parameters which gave a good visual fit to exceedance greater than $0.50\,m^3/km^2$-s. The corresponding annual yield predictions (Fig. 4B, model 2) were considerably improved over those of model *1*.

DISCUSSION

The synthetic annual yields of Fig. 4A and C, and of model 2 in Fig. 4B, all agree fairly well with observed annual yields. The agreement is somewhat surprising for Fig. 4B and C, since the sediment—discharge relation in these cases violated the model assumption of stationarity.

However, Fig. 4B and C becomes clearer after a closer look at the stationary Flynn Creek case, Fig. 4A. With the exception of the two largest values, the synthetic distribution of annual yields in Fig. 4A shows a greater variance (the graph has a steeper slope) than the observed distribution. In fact, the two largest annual yields of the 14-yr. Flynn Creek record each resulted from an extreme flood. These two floods were estimated by Harr et al.





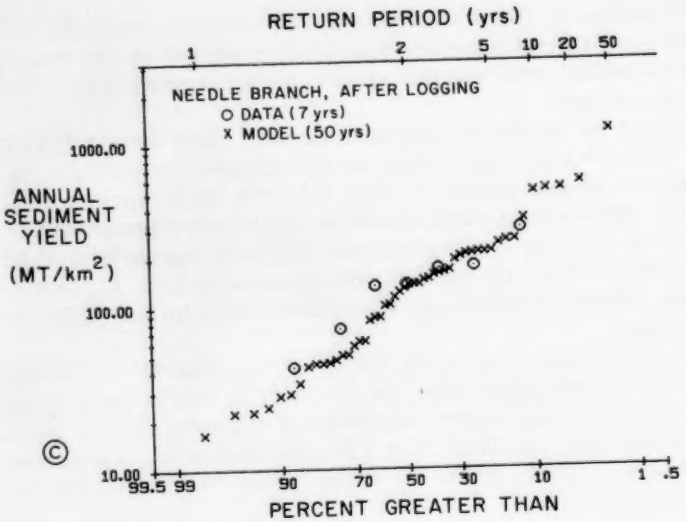


Fig. 4. Annual suspended sediment yield: (a) Flynn Creek; (b) Needle Branch — before logging; and (c) Needle Branch — after logging.

(1975) to have return periods of ~50 yr. Thus, the annual yields from these years should probably be assigned return periods near 50 yr., rather than the 14- and 7-yr. periods determined by their ranks in the 14-yr. record. If this is done, the two largest annual yields are smaller than those predicted by the model for a 50-yr. return period. This difference is consistent with the overall pattern of less variability in the observed yields than in the synthetic yields.

The difference in variability between the Flynn Creek synthetic and observed yields is evidence of controls by sediment sources, which were not included in the model. During dry years, sediment accumulated in the channel and on stream banks, and small runoff events carried a greater load than that predicted by a long-term rating curve. In contrast, the observed yields in years with large runoff events were less than that predicted by the model, probably because of the flushing effect of the first large event.

However, in Needle Branch, the sediment–discharge relation had distinct trends during both the pre- and post-logging periods. As a result, variability was added to the natural sequences of annual yields. In both cases, observed and synthetic frequency distributions appear to agree more closely than in the case of Flynn Creek. If the sediment–discharge relations in Needle Branch had been stationary, then observed annual yields would have been less variable than synthetic yields, as in Flynn Creek. Paradoxically, the predicted long-term distributions for Needle Branch (Fig. 4B and C) are probably less valid than the Flynn Creek prediction, because of the non-

stationarities. In particular, the post-logging annual yields in Needle Branch since 1972 have probably been smaller than those predicted by the model, since the sediment rating curve was determined during a period of high, but rapidly decreasing, erosion.

In their summary of stochastic sediment models, Shen and Li (1976) suggest that a deterministic relationship, as yet unknown, must exist between watershed runoff and sediment yield. However, they conclude that, for the time being, regression models should be employed to predict yields. The present study shows that the stochastically-extended regression method can synthesize reliable long-term yield distributions, as long as: (1) several years of sediment data are available; and (2) sediment supplies and yields are reasonably stationary.

In practice, both of these conditions will rarely be satisfied, and model predictions must be viewed skeptically. The key to more reliable predictions probably lies in a better quantitative knowledge of sediment sources. Such knowledge will likely take the form of a sediment budget or an erosional model (e.g., Megahan, 1974), either of which could be coupled to the sediment—discharge relation.

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